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Effect of coupled heat, air and moisture transfers modeling in the wall on the hygrothermal behavior of buildings

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Abstract

Heat and moisture exchanges between building envelope and its interior ambience are related and continued. The current state of art of the hygrothermal interactions modeling between envelope and ambience of building calls upon to dynamic simulation tools where the coupling of heat and mass transfers are generally not considered.
In this work, a hygrothermal transfer model in multilayer walls (HAM) is dynamically coupled to a thermal building model (BES). The Coupling concerns the implementation of a co-simulation between COMSOL Multiphysics©, a simulation tool in finite element for hygrothermique transfer through the envelope, and TRNSYS, a thermal simulation tool for building and dynamical systems. The HAM-BES coupling efficiency was verified by carrying out an experimental validation performed in the framework of Annex 41 of the International Energy Agency. Subsequently, a case study is conducted in order to evaluate the effect of taking into account the 1D and 2D hygrothermal transfer modeling in the envelope on the global thermal and hydric behaviors of the building. Results confirm the direct impact of modeling the coupled heat, air and moisture transfer through the envelope on the overall hygrothermal behavior of buildings.

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Keywords: Hygrothermal modeling, dynamic simulation, HAM-BES co-simulation, Eneggy consumption

1. Introduction

In order to reduce energy costs and environmental impacts related to buildings, several organizations and research laboratories have focused on the physical study of the building and its energy behavior. These studies allow creating

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different approved modeling tools for the thermal and hydric study of building as TRNSYS and Energy plus. However, the coupled heat, air and moisture transfers in the walls are generally badly represented.

To overcome this problem, and be able to better stimulate hygrothermal behavior of buildings, several approaches were proposed in recent years. Among these approaches the co-simulation, which consists to cohabit two existing softwares, one for dynamic building simulation and the other for accurate modeling of hygrothermal behavior at the envelope. The concerned approach allows a better description of heat and moisture transfer through hygroscopic walls as an integral part of the building. In this sense, the literature reported a number of previous works among which are mentioned, hereinafter, the most important.

Nomenclature

i	Layer position in the wall from the outside to inside
T	Temperature [K]
P_v	Water vapour pressure [Pa]
P	Total pressure [Pa]
t	Time [s]
q_s	Dry density [kg/m^3]
C_m	Storage moisture capacity [kg/(kg.Pa)]
C_p	Heat capacity [J/(kg.K)]
L_v	Evaporation latent heat [J/kg]
ß	Thermal conductivity [W/(m.K)]
C_a	Humid air Capability [s^2/m^2]
k_m	Total moisture permeability [kg/(m.s.Pa)]
k_T	Liquid water conductivity caused by temperature gradient [kg/(m.s.K)]
k_P	Moisture infiltration coefficient [kg/(m.s.Pa)]
y, α	Heat convection coefficient due to a water vapor pressure gradient and a total pressure gradient respectively [m^2/s]
o	Ratio between water vapor exchange mass and the overall mass exchange [-]

Tariku et al. [1] have developed a simulation environment under SimuLink named HAMFitPlus, which integrates both hygrothermal transfer models for the envelope and indoor of building. Steeman et al. [2] have conducted an integration of a 1D HAM model in a BES software (TRNSYS) for modeling the hygrothermal transfer in porous building materials. This could be achieved by coupling the HAM model equations to those of TRNSYS.

However, in the majority of carried out works in this subject, 2D and 3D modeling of coupled heat and moisture transfer is not taken into account. In this paper, a model of coupled heat, air and moisture transfer in multilayer walls was established. Subsequently, in order to study wall hygrothermal transfer effect on building energy consumption, an integration approach of envelope coupled heat, air and moisture transfer model (HAM) in a building simulation code (BES) was undertaken. Finally, a case study was conducted to analyze the influence of considering coupled heat, air and moisture transfer through wall on indoor air hygrothermal behavior and building energy consumption.

2. Coupled heat, air and moisture transfer modeling in the building envelope

In order to have an accurate prediction of the hygrothermal behavior at the building envelope, we have opted for a model based on the Luikov theory [3]. The developed model, consider temperature as driving potential for heat transfer, total pressure for air transfer and water vapor pressure for the hydric transfer. This allows us to avoid discontinuity problems at the wall layers interfaces, which is not the case with the water content [4].

To realize an accurate study, we took into account in this approach, the variation of hygrothermal material properties depending on the water content. This concern especially, the moisture permeability and the storage moisture capacity for hydric transfer, the thermal conductivity for heat transfer. Equations (1), (2) and (3) represent respectively balances of mass, gaseous and heat.

$$C_{m_i}\rho_{s_i}\frac{\partial P_v}{\partial t} = div\left(k_{m_i}\nabla P_v + k_{T_i}\nabla T + k_{p_i}\nabla P\right) \quad (1)$$

$$C_{a_i}\frac{\partial P}{\partial t} = div(k_{p_i}\nabla P) \quad (2)$$

$$C_{p_i}\rho_{s_i}\frac{\partial T}{\partial t} = div\left(\lambda_i\nabla T + \alpha_i\nabla P_v + \gamma_i\nabla P\right) + L_v\rho_{s_i}C_{m_i}\frac{\partial P_v}{\partial t} \quad (3)$$

3. HAM-BES co-simulation approach

The co-simulation approach consists on coupling a dynamic building simulation tool (TRNSYS) with a coupled heat, air and moisture transfer model implemented in COMSOL. The coupling was carried out through MATLAB which represents an integrator tool ensuring the data exchange between TRNSYS and COMSOL.

Indeed, TRNSYS is used here because it is widely used by scientific community and by engineers. In addition, its modular architecture is an advantage because it allows extending the modeling to a thermo-hydro-aeraulic modeling. This is achievable by integrating ventilation types in simulations as Comis or Contam. For the hygrothermal transfer simulation in the building's walls, COMSOL was chosen in order to have an enough fine granularity simulation to describe the hygrothermal transfer in 2D and 3D especially in specific envelope components involving multidirectional flows such as thermal bridges.

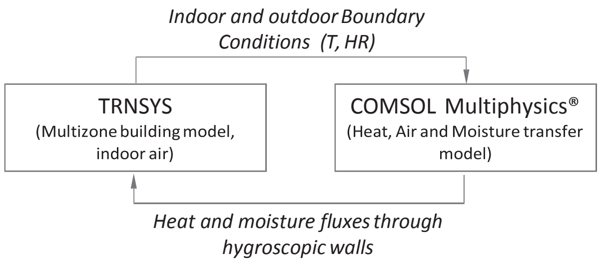

Figure 1: Dynamic co-simulation approach between HAM (COMSOL) and BES (TRNSYS) models

The COMSOL/MATLAB connection is provided through the LiveLink interface [5]. Thus, the HAM model is defined in MATLAB and differential equations system is solved by the COMSOL solver. Concerning the TRNSYS/MATLAB link, it is established using the type 155 [6].

In this approach, the control of the time step was provided by the BES model (TRNSYS). Consequently, the data exchange between the two coupled softwares is made in the post-convergence to the current BES model time step during which the HAM model is solved in COMSOL with a finer time step. The diagram in Figure 1 summarizes the temporal synchronization approach and data exchange strategy between the BES model in TRNSYS and the HAM model in COMSOL.

3.1. HAM-BES platform validation

In order to verify the correct functioning of the HAM-BES dynamic co-simulation in a realistic configuration, an experimental validation was conducted by comparing the HAM-BES coupled model with experimental data extracted from the test results published by the International Energy Agency IEA as part of Annex 41.

In this validation, the EC3 experimental test of Annex 41 was considered. This test was carried out by the Fraunhofer Institute for Building Physics in Germany [7]. The test was performed on a room with volume of 50 m^3. All details about the experiment are mentioned in the final report of Annex 41 [8].

Figure 2 shows the comparison between experimental data and numerical simulation for the period of January 17 to 19, 2005. There is a good agreement between the experimental results and the numerical prediction obtained by the coupled HAM-BES model.

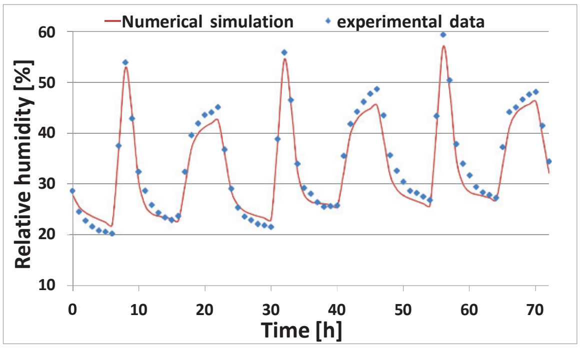

Figure 2: Comparison of numerical simulation of HAM-BES model and experimental data of annex 41 (17 to 19 January 2005)

4. Case study

After validation, the developed HAM-BES co-simulation platform was applied to analyze the impact of 1D and 2D wall hygrothermal transfer modeling on thermal and hydric behaviors of inside air building as well as its energy consumption. For this purpose, a case study was carried out by considering experimental building used for the HAM-BES co-simulation platform validation described in preceding paragraph. In this study, three dynamic simulations approaches were considered, details of simulation cases are summarized in Table 1.

Table 1 : Description of simulation cases

Simulation case	
Case A.1	TRNSYS dynamic simulation model
Case A.2	TRNSYS model + 1D HAM model for envelope
Case A.3	TRNSYS model + 1D HAM model (envelope) + 2D HAM model (upper thermal bridge)

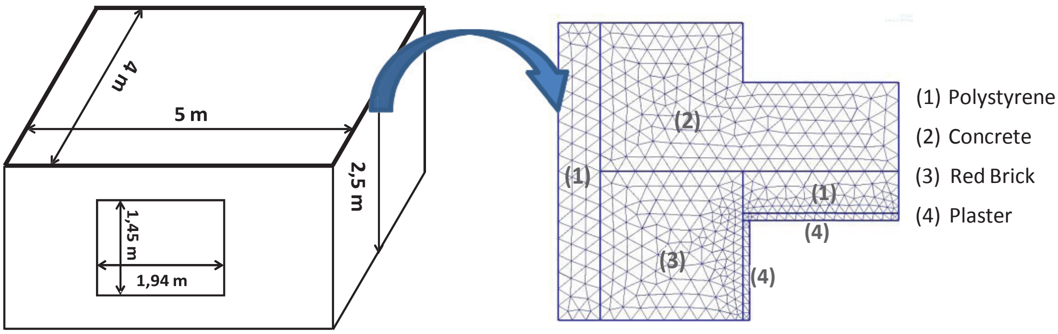

Figure 3: Geometry of the test building and composition of studied upper thermal bridge

In the first simulation case, the linear correction term to take into account of heat flux contribution of thermal bridge is considered. This coefficient is determined according to European standards EN-ISO 14683. For the second case, the dynamic co-simulation platform is used with 1D HAM transfer model for the envelope. In the third case simulation, in addition to 1D hygrothermal transfer model for current walls, multidimensional effect is considered by modeling hygrothermal transfer in 2D with finer granularity (see Figure 3).

Case study building is supposed to be transferred to La Rochelle. The simulations cases described in Table 1 were applied for both winter (January) and summer (August) periods. For this, hygrothermal control systems (heating and cooling) were imposed. Set temperature was fixed at 18°C in winter and 26°C in summer. For relative humidity, the comfort zone between 35% and 65% was imposed for two seasons. The same initials conditions are considering for both envelope and internal ambiance of the building (T_0=20°C and HR_0=50%).

Relative humidity and temperature profiles of inside building are represented in Figure 4 for summer period. Large temperature difference is observed between case A.1 (TRNSYS model) and two other cases A.2 and A.3 where difference is less important.

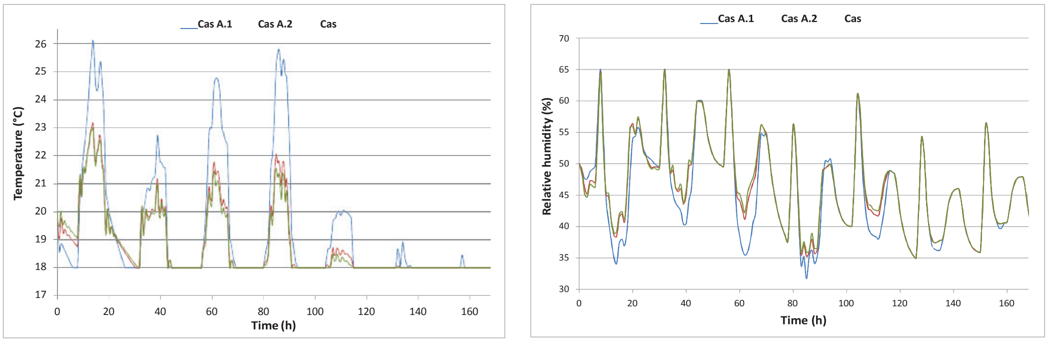

Figure 4: Inside hygrothermal behavior (1st – 7 January)

This behavior is due to the integration of the hygrothermal transfer model which involves the consideration, in addition to thermal conduction, a convection phenomenon caused by water vapor pressure gradient of both sides of envelope, a latent heat and thermal conductivity variation due to the presence of the vapour.

For relative humidity profiles, same behavior is noted with a gap between case A.1 compared to cases A.2 and A.3. This different hygrothermal behavior illustrates clearly the impact of taking into account moisture transfer in building envelope as well as water vapor adsorption/desorption effect in inner envelope surface.

The observed difference in heat and relative humidity profiles between cases A.2 and A.3 is explained by the multidimensional effect considered in case A.3, where additional hygrothermal flows are input in global energy and mass balances.

4.1. Effects of hygrothermal transfer on building energy consumption

Consideration of hygrothermal transfer at building envelope in dynamic building simulation has a considerable effect on prediction of energy consumption. However, there is a little works in this sense [9]. Among carried out studies, Qin et al. works [10], who have analyzed effect of hygrothermal-air flow transfer on building energy consumption. In this section, our study extends, in addition to hygrothermal transfer impact of envelope, to a multidimensional effect by modeling hygrothermal transfer phenomenon in 2D for upper thermal bridges.

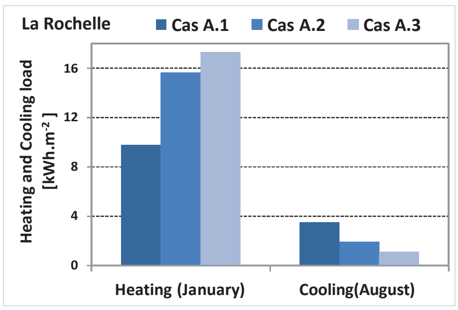

Figure 5: Energy consumption (heating and cooling)

Energy consumption was calculated for the studies cases carried out in the previous section (see Table 1). Figure 5 summarizes energy needs of heating (January) and cooling (August).

In the heating season, energy consumption prediction of TRNSYS model is lower than the two other models where hygrothermal transfer through envelope is included. Difference between TRNSYS model and the one that take into account of 1D hygrothermal transfer reaches 32.43%.

This significant underestimation in heating energy consumption for TRNSYS model highlights importance of considering coupled heat, air and moisture transfer modeling in dynamic building simulation.

When hygrothermal transfer modeling is performed in 2D for upper thermal bridges, the difference of heating load is more important compared to TRNSYS model. Underestimation reached 40.83%. This result is explained by consideration of multidimensional effect in hygrothermal bridges modeling where heat losses become more important.

In the cold season, cooling loads are less important. Nevertheless, comparing the three studied models, an overestimation in TRNSYS model is occurred that reached 51% compared to model that consider both 1D and 2D hygrothermal transfer modeling. This behavior can be explained by external climatic conditions that imposed thermal flow to the inner and convection thermal flow in opposite direction which reduced heat grains from the wall for the two models where the hygrothermal transfers are considered.

5. Conclusion

Coupled heat, air and moisture transfer through envelope has a significant impact on hygrothermal indoor behavior and energy consumption. In this work, a hygrothermal transfer model in multilayer wall was established. This phenomenon is modeled in 1D for walls and 2D for thermal bridges to take into account of multidimensional hygrothermal transfer effect of these envelope elements.

In order to illustrate the influence of considering wall hygrothermal transfers on the prediction of building energy consumption, HAM-BES a dynamic co-simulation platform was developed. The advantage of this platform is a dynamic connection between both HAM and BES models that ensures continuous interaction between envelope and indoor hygrothermal behaviors.

After proceeding to an experimental validation of HAM-BES co-simulation platform, a case study was carried out. In the simulations cases, results showed that the consideration of the coupled hygrothermal transfer through the envelope walls has an important impact in terms of building energy load prediction. Moreover, the results showed the effect of the multidimensional hygrothermal transfer modeling in thermal bridges which involves additional wall heat and moisture flows in indoor mass and energy balances and affects the building energy loads.

Acknowledgements

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